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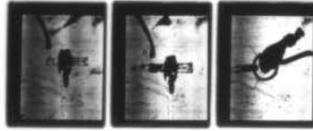
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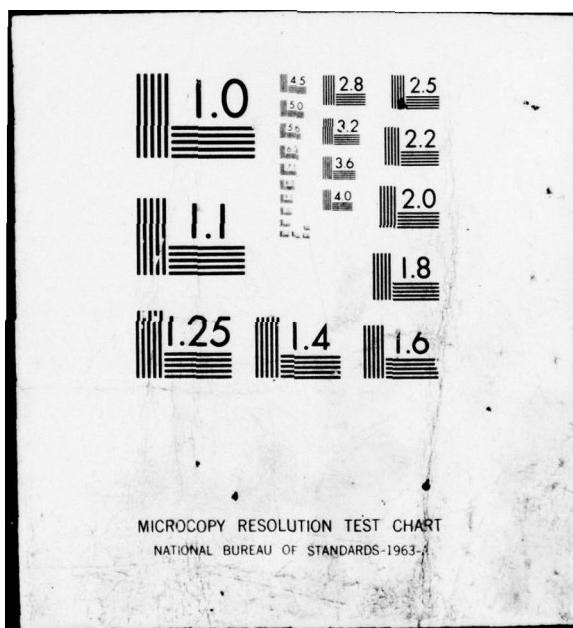
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A new method is described for simplifying the design and construction of inductively coupled plasma torches. In the method, tap water is directed into the torch's gas inlet tubes and the swirl pattern of the exiting liquid is observed. From this pattern, irregularities in the torch can be readily noted and operating behavior of the plasma can be predicted.			

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TECHNICAL REPORT NO. 21

HYDRODYNAMIC FLOW PATTERNS AS A SIMPLE AID TO EFFECTIVE

ICP TORCH DESIGN

by

Earl Sexton, Richard N. Savage and Gary M. Hieftje

Prepared for Publication

in

APPLIED SPECTROSCOPY

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In the past five years interest has soared in the inductively coupled plasma (ICP) as an excitation source for optical emission spectrochemical analysis. As a result, the ICP has rapidly made the transition from research laboratory to industrial application facility and the number of ICP users has grown correspondingly. This report describes a simple yet effective technique to aid users in constructing, modifying and repairing the most important component in their ICP system--the plasma torch.

The heart of every ICP system is the specially arranged quartz tubes which comprise the plasma torch. It is the unique gas flow patterns produced by this device which enable a plasma to be easily ignited and sustained and to accept sample. Unfortunately, the critical parameters in torch construction have not been clearly defined and the fabrication of a functioning torch is an art which few have been able to master. In an attempt to construct highly efficient miniaturized ICP torches in our laboratories, we have developed a diagnostic method for evaluating critical parameters in torch design. The technique is based on hydrodynamic principles and has enabled us to evaluate and build our own torches with a minimum amount of effort and a high rate of success. This capability can result in a significant savings for users since torch damage frequently occurs during routine operation.

According to Reed¹ and others^{2,3} the key to a successful torch lies in its ability to create a vortex in the support gas (typically argon or nitrogen) flowing through the torch. It is the creation of a low-pressure zone within the vortex which enables a plasma to be formed and stabilized in the end of the torch. However, because the support-gas vortex cannot

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be seen, it has been difficult to determine exactly which parameters in torch design influence vortex formation. We have observed that by introducing a stream of water into a properly designed torch in the same fashion as would the support gas, one can visually observe the formation of a vortex. By repeatedly modifying torch construction and observing the influence each change has on the effectiveness of the torch at forming a vortex, one can empirically determine which parameters are important in torch design. Once the important parameters are known it becomes easy to build a torch which will operate properly. In fact the person involved in actually building the torch can use the hydrodynamic technique during each stage of torch construction as a quick means of determining if the pieces have been properly assembled. Using this technique we were able to construct the miniature torch shown in Fig. 2 of reference 4. This torch will sustain a mini-plasma at low RF power levels and with reduced amounts of argon support gas with no deterioration in analytical capability; thereby increasing its efficiency.⁴

The photograph in Fig. 1 illustrates the flow pattern produced when water is introduced into the coolant gas inlet tube of a properly constructed miniature torch. As the water spirals through the torch, a well-shaped vortex is created in the end of the torch just above the plasma tube. Then, as the spiraling water exits the torch, an umbrella-shaped spout is generated. These characteristic patterns will only be developed by a properly constructed torch. Typically the water is introduced into either the coolant or plasma gas inlet tubes at a rate of approximately 900 ml min^{-1} (for a torch with a 14 mm o.d. coolant tube); of course this flow should vary with torch size.

Now, using flow patterns of this nature let us evaluate the critical features in torch design. All of our discussion will refer specifically to the miniature torch we developed.⁴

One of the most important features in torch construction is the tangential orientation of the gas inlet tubes. Reed¹ was one of the first to recognize that the surest way to establish a vortex is to orient the inlet tubes of a torch so that their central axes lie on tangent lines to the coolant tube. If the plasma and coolant gas inlet tubes are properly oriented in this manner, water introduced through these tubes will be forced to spiral up through the torch and will produce a vortex as shown in Fig. 1. However, if the inlet tubes are improperly oriented, a pattern such as the one in Fig. 2 will be generated. With the new method it is easy to empirically optimize the position of the inlet tubes; one simply changes their orientation until the water is forced to spiral up through the torch at the highest swirl velocity possible.

Internal diameters of the inlet tubes are also important in torch design.^{3,4} Not surprisingly, smaller i.d. tubes increase the swirl velocity of the water as it spirals up the torch. Accordingly a stable vortex could be formed at lower water flow rates, indicating that a savings in support gas consumption could also be realized. Significantly, there appears to be a limit to the amount the inlet tubes can be constricted. We observed with our miniature torch that inlet diameters less than 2 mm produced unstable flow patterns. Apparently, if the introduction velocity is too high, the water does not form a stable spiraling pattern but becomes non-uniform, resulting in a turbulent flow similar to the one demonstrated in Fig. 2.

Another important parameter in torch design is the shape of the intermediate or plasma tube. We have observed that a flared plasma tube such as the one ordinarily used creates an excellent vortex. Fig. 3A demonstrates the hydrodynamic pattern created in a torch with a straight plasma tube (8 mm o.d.). Notice the small and confined vortex which is created. We also observed that if a 10 mm o.d. straight plasma tube was employed in our 14 mm mini-torch, the spiraling nature of the water was distorted and a more turbulent condition arose. In Fig. 3B is shown the flow pattern for a flared shaped plasma tube. Clearly, a better vortex is created with the flared design as evidenced by the larger, more well defined hole created in the tip of this torch. By observing flow patterns such as these, we concluded that a 4 mm gap between the plasma and coolant tubes in the lower part of the mini-torch is necessary to ensure that a stable spiraling flow pattern is established; a 2 mm gap between the flared out portion of the plasma tube and the coolant tube then constricts the water path and increases flow velocity which enhances vortex formation. Moreover, this design directs the flow against the inner wall of the coolant tube and thereby provides maximum thermal isolation for the torch. If the distance between the coolant and the flared portion of the plasma tube is decreased below 2 mm then the velocity of the water exiting the mini-torch becomes too high and an unstable flow pattern is produced.

We also noted that it is easier to ignite and sustain a low-power plasma with a torch employing the flared plasma tube design. Other investigators have come to this same conclusion.⁵ One possible explanation can be derived from hydrodynamic theory, which predicts that a fluid flowing through a flared shaped tube of this design will produce sheds vortices.⁶

In other words, as the fluid moves through the torch, that part which is in contact with the plasma tube will be slowed down as it flows around the flared portion, relative to the fluid which is traveling along the inner wall of the coolant tube. As the fluid flowing along the plasma tube passes the end of the tube, some of it will break off from the mainstream and flow in the opposite direction. Indeed, it has been shown⁷ that a counter or reverse flow of this nature facilitates plasma ignition and stability.

Another important feature of the plasma tube is its length beyond the flared region (i.e., the length of the 10 mm o.d. portion of the plasma tube in Fig. 2 of ref. 4). If this section is too long, water will shoot straight out of the end of the torch and collapse inward toward the central axis of the torch instead of breaking off sharply into an umbrella-shaped spout (cf. Fig. 1). We have observed that torches which flow patterns of this type do not produce stable plasmas. When this section of the plasma tube is of the appropriate length (11 mm for the miniature torch in Fig. 2 of ref. 4) the umbrella-shaped spout shown in Fig. 1 will be formed. If the length is too short, the spiraling flow of water directed towards the inner wall of the coolant tube by the flared portion will not be properly confined and will bounce off the walls, producing a turbulent flow condition.

A final important feature in ICP torch construction is the concentricity of the tubes. If the plasma and coolant tubes are not aligned concentrically, a distorted water flow pattern such as the one in Fig. 4 will result. Instead of the water forming a symmetrically shaped spout it will be noticeably skewed. Concentric alignment can be assured during torch construction by placing a precisely machined graphite sleeve between the coolant and plasma

tubes. This technique can also be employed to ensure that the sample injection tube is concentrically aligned.

ACKNOWLEDGEMENT

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7. C. D. Allemand and R. M. Barnes, Appl. Spectrosc., 31, 434 (1977).

FIGURE LEGENDS

Figure 1. HYDRODYNAMIC FLOW PATTERNS PRODUCED BY A PROPERLY CONSTRUCTED MINI-TORCH.

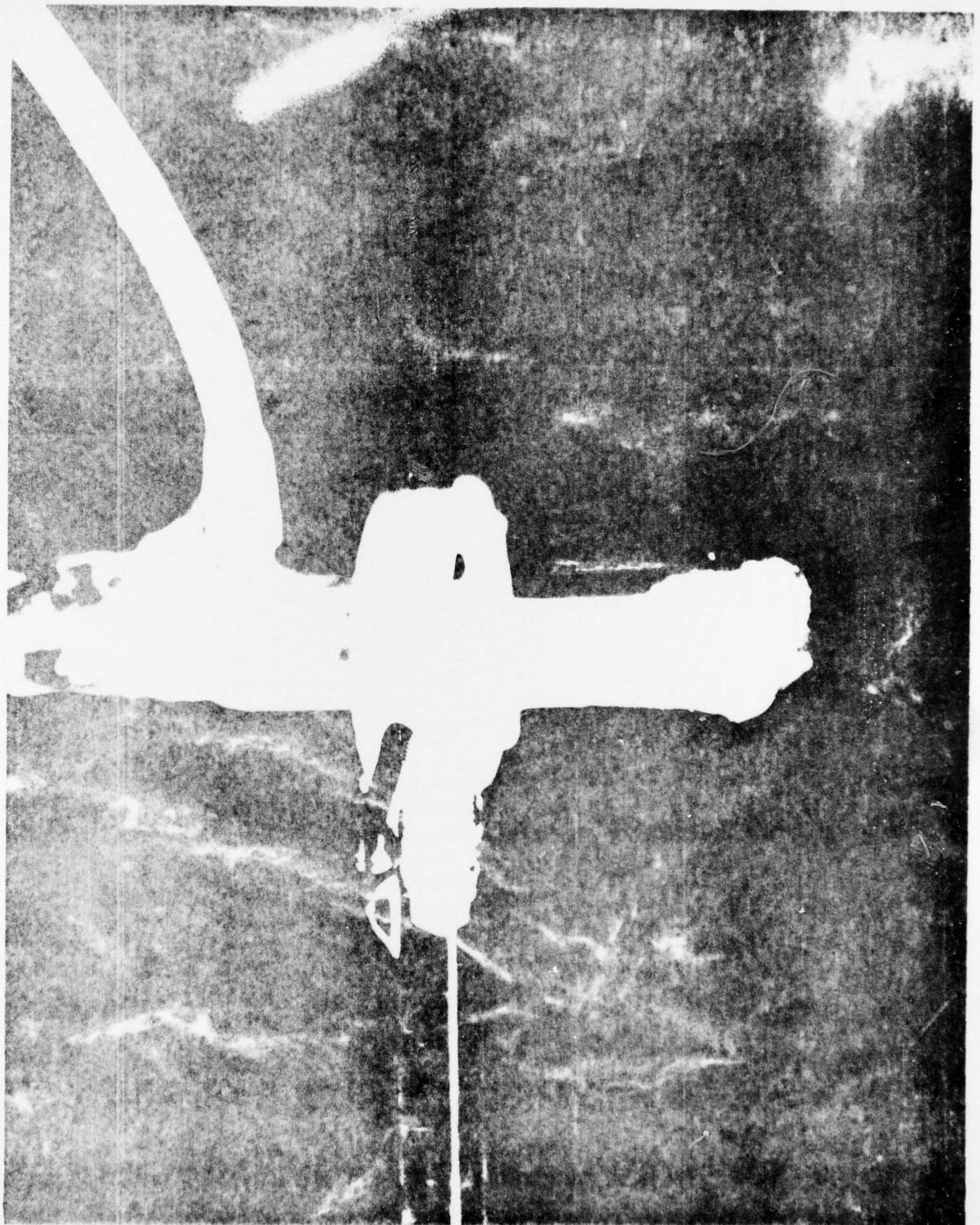
Figure 2. FLOW PATTERN ESTABLISHED WHEN COOLANT GAS INLET TUBE IS NOT TANGENTIALLY ORIENTED.

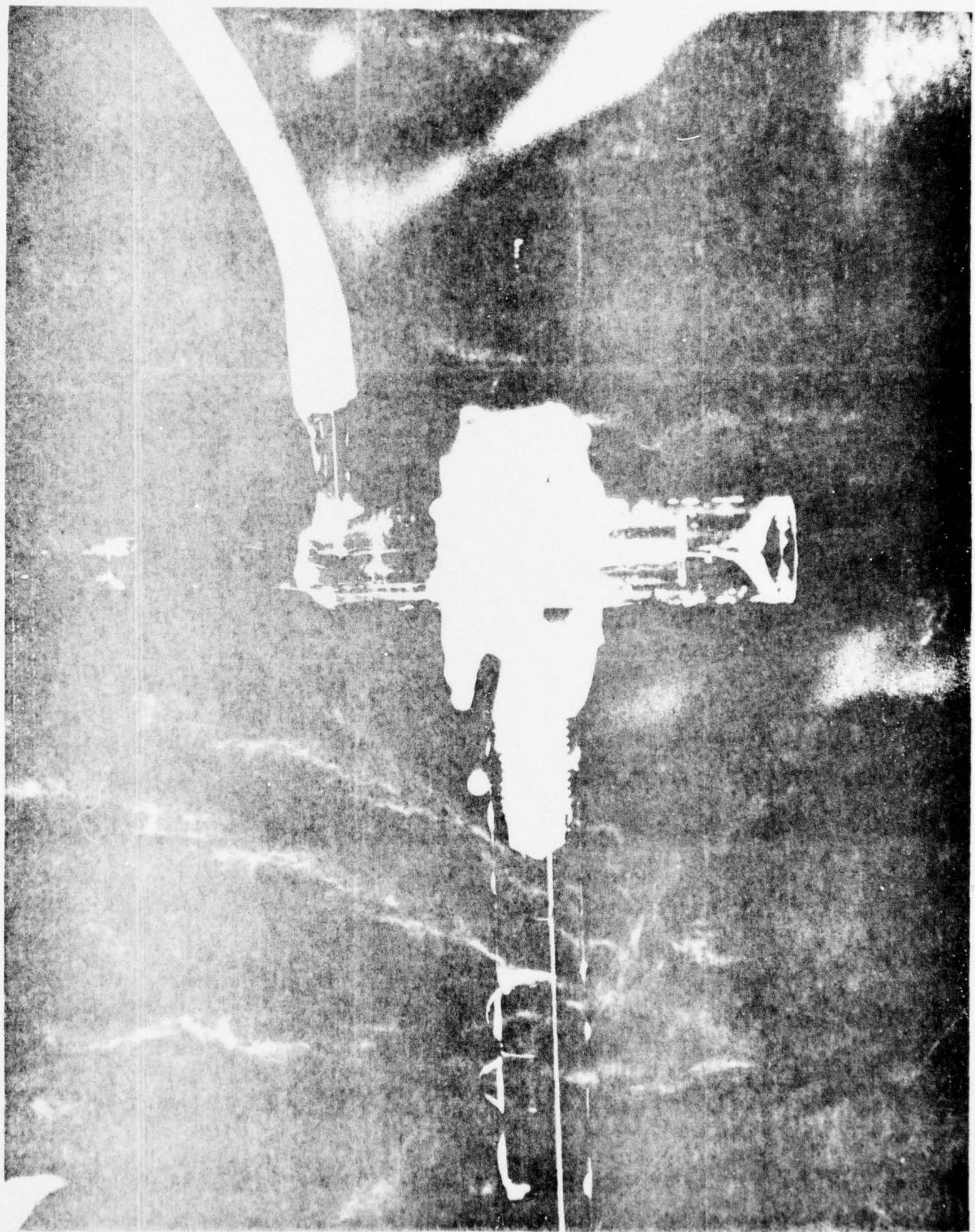
Figure 3. EFFECT OF PLASMA TUBE SHAPE ON VORTEX FORMATION. In both cases water is introduced into the coolant gas inlet tube. However, the torch in Fig. 4A was not equipped with a plasma gas inlet tube.

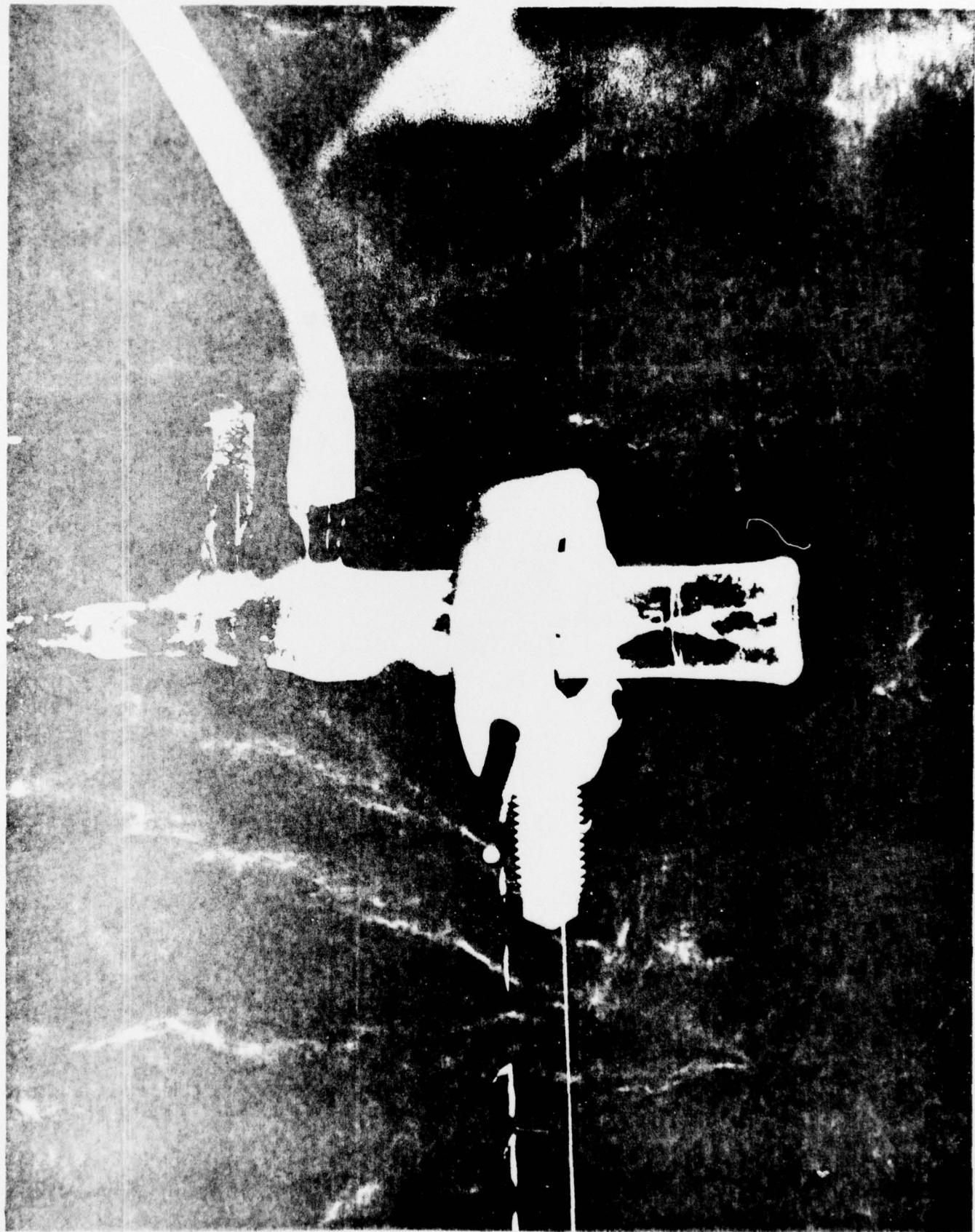
- A. Straight Design
- B. Flared Design

Figure 4. WATER FLOW PATTERN PRODUCED BY NON-CONCENTRIC TORCH











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